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EVALUATION OF RADIATION CONDITIONS ON THE LUNAR SURFACE *\/1

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An estimate of the level of penetrating radiation on the surface of the moon and of the possible radiation hazards for astronauts is attempted. Levels of radiation from all sources are tabulated, indicating that main radiative action would be from galactic cosmic radiation (GCR) and from solar corpuscular radiation (SCR) which latter is more intense during solar chromosphere flares. Protective clothing (light-atom shields of 15 gm/cm^2 thickness) and shelters built of lunar soil of about 100 gm/cm^2 thickness would lower the tissue dose received from GCR by a factor of 3 - 4 and from SCR to 10 ber.

Author

It is of interest to estimate the levels of penetrating radiation on the surface of the moon. Knowledge of these factors would be of importance both for predicting possible radiation hazards for astronauts on the lunar surface (Bibl.1 - 4) and for determining the possible effect of radiation on various design and structural materials to be used under lunar conditions (Bibl.5). It must be emphasized that estimates of this kind can be merely of an orientating nature until direct measurements can be made.

As a result of the almost complete absence of atmosphere and magnetic field on the moon, its surface is constantly being bombarded by fluxes of charged particles, consisting mainly of galactic cosmic radiation and solar corpuscular

*Numbers in the margin indicate pagination in the original foreign text.

radiation. The galactic cosmic radiation (GCR) consists mainly of protons (85% of the flux), alpha-particles and heavier nuclei with energies up to about 10^4 Gev/nucleon. A calculation made by the method given elsewhere (Bibl.6) shows that the fluxes of GCR in interplanetary space would produce, in the body of a human subject protected by a light-atomic shield of 1 gm/cm^2 thickness, a mean tissue dose of 100 - 250 mber/day (the mean tissue dose is the integral dose absorbed by the whole body divided by its mass). With increasing thickness of the shield, up to about 15 gm/cm^2, the dose remains practically constant.

Because of the isotropy of the angular distributions of the GCR fluxes, the dose due to this radiation on the lunar surface will be half that in space, i.e., about 50 - 130 mber/day, depending on the period of solar activity. /2

Bombarding the surface of the moon, the GCR activates its rocks and causes the formation of secondary particles. The radiation levels due to secondary radiation, according to estimates by Barton (Bibl.7), amount respectively to 0.12×10^{-3} ber/week from secondary neutrons and 0.37×10^{-3} ber/week from secondary γ-radiation.

The greatest hazard to an astronaut on the moon is produced by solar corpuscular radiation (SCR) accompanying some solar chromospheric flares.

The frequency of appearance of SCR is connected with solar activity. During the period of maximum activity there are about 5 to 13 flares of SCR per year, while in the period of minimum activity their frequency decreases considerably. Accordingly, flares of SCR are rarely observed in the present period of minimum solar activity (1964 - 1966) and will presumably be more frequent in the next period (1969 - 1970).

Measurements of the composition and spectrum of the SCR have shown that most of the flux of charged particles consists of protons with energies in the range from hundreds of Kev to several Gev. Alpha-particles and heavier nuclei are also observed in the composition of the SCR.

The total duration of a flare may vary from several hours to tens of hours. The degree of anisotropy of the angular distributions of radiation likewise depends on the localization of the flare and the state of the magnetic fields in interplanetary space. The question of the anisotropy of the SCR fluxes has not yet been sufficiently investigated. According to present concepts, this anisotropy is slight, so that the dose produced by the SCR on the lunar surface would be only half as great as in space.

The doses and their attenuation, as a function of the thickness of the protective shield, were calculated in accordance with the technique given by Bobkov (Bibl.8).

In exactly the same way as in the case of GCR, radioactive isotopes are formed as a result of nuclear interaction of SCR with the matter of the lunar surface. Here, as a result of the action of SCR, a considerably greater induced radioactivity will be produced than from the action of GCR. This results from the fact that the integral intensity during the period of maximum solar activity for GCR and SCR will be, respectively, 10^8 particles/cm^2 and 10^{11} protons/cm^2 per year.

The extent of radioactivity induced under the influence of the charged particles is a function of the flux of particles impinging on the target, the number and species of the target nuclei, and the reactive cross section for formation of the given isotope:

As a model for the particle spectrum we used the proton spectrum from the /3 flare of November 12, 1960 which is very typical and the best studied of all flares. We used two models for the element content in the outcropping rocks of the moon: one analogous to the terrestrial composition, and one corresponding to the mean meteorite composition. On the basis of the abundance of the elements, we used the cross sections for reactions of protons with oxygen, aluminum, iron, silicon, magnesium, and sodium. In evaluating the field of reactions studied, we disregarded the following:

Formation of isotopes with a half-life of less than 10 min, since the size of the dose due to induced radioactivity of rapidly decaying isotopes will be appreciable only during a flare, at which time the dose due directly to the protons of the solar flares will be several orders larger.

Reactive cross section less than 5 mbarn (the total cross sections for inelastic collisions with the nuclei usually amount to hundreds of mbarn).

Reactions with thresholds above 50 - 100 Mev, since the differential proton spectrum of solar flares can be approximated by a law of exponents $E^{-\gamma}$, where $\gamma = 2 - 5$ (Bibl.9).

Under these assumptions, we calculated the induced radioactivity for a sequence of thin layers of the upper strata of the moon, taking account of its isotopic composition and of the deformation of the proton spectrum for various thicknesses. We then determined the dose at the end of the flare from the resultant semi-infinite plane source, whose specific activity declines rapidly with depth. Here, of course it was necessary to consider the consequences of preceding flares, especially for the long-lived isotopes. Under the assumption that the flares take place regularly with a definite frequency (high-intensity flares once a year, flares of moderate intensity once a month), we estimated the constant background due to long-lived isotopes, which was found equal to terrestrial and meteoritic models of 5×10^{-6} ber/hr and about 9×10^{-6} ber/hr.

The results show that the level of radioactivity in general depends only slightly on the isotopic composition of the lunar rocks. Between the two cases - the terrestrial and meteoritic models - the radiation levels due to induced radioactivity differ by a factor of two. This permits us to assert that the possible deviation of the composition of the upper crust of the moon from the models used in the calculation will not much change the results.

One of the radiation sources on the lunar surface might be the natural radioactivity of its upper rocks.

For a rough estimate of the radiation levels due to this source, let us use the following considerations: Studies of the radioemission of the moon in the short-wave range (Bibl.10) have shown that the composition of the lunar rocks is close to that of terrestrial rocks. It is therefore reasonable to assume /4
the same concentration of natural radioactive elements as on the earth. Under these assumptions, the dose due to natural radioactivity will be $6 \times 10^{-6} - 8 \times$ $\times 10^{-5}$ ber/hr.

It is not impossible that the upper layer of the lunar surface is covered by meteoritic matter to a depth of 10 cm. This would mean a lower dose due to natural radioactivity, since the concentration of radioactive elements in meteoritic matter is about one tenth that in terrestrial rocks.

The radiation levels from all sources considered are given in the Table.

It will be clear from the data of the Table that the SCR is a serious health hazard for the astronaut. The radiation levels due to the SCR may be substantially lowered if the astronaut is housed in a special shelter during the

flare. The protection for this shelter could be built of lunar soil, which closely resembles aluminum in its protective properties. Rough estimates indicate that the mean $\bar{Z}$ of lunar matter is 12 - 16. Based on 0.5 gm/cm^3 for the density of the upper rocks of the moon (Bibl.10), shelter walls of 2 m thickness (about 100 gm/cm^2) would lower the dose from the SCR flare of February 23, 1956, which contained protons of the highest energy, to 10 ber. The same shelter /5
would decrease the dose from the GCR by a factor of about 3 - 4.

RADIATION LEVELS ON THE LUNAR SURFACE

Source of Radiation	Dose	Time of Action	Remarks
Direct radiation of solar flares Feb. 23,1956 October 12,1960 May 10,1959	340 (surface dose) 50 (tissue dose) 1600 (surface dose) 70 (tissue dose) 6600 (surface dose) 220 (tissue dose)	2 - 3 days 4 years 2 - 3 days one year	These doses behind a shield of 1 gm/cm^2 (ber after flare)
Induced activity from solar flares	$(2\text{-}6) \times 10^{-5}$ $(5\text{-}9) \times 10^{-6}$	1 day after flare and equilibrium dose	Flare of Oct.12,1960
G C R	$(2\text{-}5) \times 10^{-3}$	Constant	Mean tissue dose indicated
Secondary neutrons from G C R	7×10^{-7}	Constant	Local dose indicated
Natural radioactivity	$6 \times 10^{-6} - 8 \times 10^{-5}$	Constant	Local dose indicated

The dose received by an astronaut on the lunar surface would naturally depend on the length of his stay there. An increase in his stay from one day to 30 days would increase the absorbed dose from 50 - 130 mber to 2 - 4 ber (not including the SCR). For the same periods, the probability of a high-intensity flare would rise from about 0.3% to about 10% (during a period of maximum solar activity).

Thus, it may be stated that the stay of a human being on the lunar surface, as far as radiation danger is concerned, differs from his stay in a spacecraft during orbital flight only in that a shelter could be built on the moon. In both cases, however, the radiational effect is due primarily to SCR and GCR. Improvement of the radiation conditions should therefore proceed primarily along the line of a more complete and careful study of the composition, spectra, and time variations of both SCR and GCR.

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